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9 AUTHORS, INCLUDING:


Ji-Qin Ni
Purdue University

Bill W. Bogan
Purdue University

Albert Heber
Purdue University


Teng T. Lim
University of Missouri

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Characteristics of ammonia, hydrogen sulfide, carbon dioxide, and particulate matter concentrations in high-rise and manure-belt layer hen houses

Ji-Qin Ni*, Lilong Chai [1], Lide Chen [2], Bill W. Bogan, Kaiying Wang [3], Erin L. Cortus [4], Albert J. Heber, Teng-Teeh Lim [5], Claude A. Diehl

Dept. of Agricultural and Biological Engineering, Purdue University, 225 S University St., West Lafayette, IN 47907, USA

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abstract

Indoor air pollutants at high concentrations in poultry houses can potentially affect workers' health, and animal welfare and productivity. This paper presents research results of a 2-year continuous monitoring of ammonia (NH_3), carbon dioxide (CO_2), hydrogen sulfide (H_2S), and particulate matter (PM) concentrations from to date the most comprehensive study on a single farm in two 180,000-bird high-rise (HR) and two 200,000-bird manure-belt (MB) layer hen houses located in Indiana, USA. Air was sampled at ventilation fans of the mechanically-ventilated houses. Concentrations of NH_3 and CO_2 were measured with photoacoustic multi-gas monitors. Concentrations of H_2S and PM_{10} were monitored with pulsed fluorescence analyzers and Tapered Element Oscillating Microbalances (TEOM), respectively. The 2-year mean standard deviation concentrations at ventilation fans of the four layer hen houses were 48.9 39 and 51.9 40.7 ppm in HR, and 13.3 9.1 and 12.9 10.5 ppm in MB for NH_3; 26.4 17.6 and 24.9 19 ppb in HR, 40.0 21.1 and 41.2 31.5 ppb in MB for H_2S; 1755 848 and 1804 887 ppm in HR, and 2295 871 and 2285 946 ppm in MB for CO_2; and 540 303 and 552 338 $\mu g\ m^{-3}$ in HR, and 415 428 and 761 661 $\mu g\ m^{-3}$ in MB for PM_{10}. Compared with the MB houses, concentrations of the HR houses were higher for NH_3, and lower for CO_2, H_2S, and PM_{10} ($P < 0.05$). High concentrations of NH_3 detected in winter represent potential challenges to workers' health and animal welfare. Variations in pollutant concentrations at the exhaust fans were affected by outdoor temperature, ventilation, bird condition, and farm operation. A new weekly variation, characterized by significantly lower PM_{10} concentrations on Sundays, was identified and was related to the weekly schedule of house operational activities.

1. Introduction

Air pollutants, including gases and particulate matter, in poultry houses can cause indoor air pollution and affect health and welfare of the birds, production efficiency, and environmental sustainability. Controlling the living space environment, particularly temperature, humidity, air quality, and litter quality is crucial to poultry welfare (e.g., Dawkins et al., 2004). High concentrations of gases, e.g., ammonia (NH_3), inside animal houses represent potential health hazards to humans and animals (Portejoie et al., 2002). Hydrogen sulfide (H_2S) is one of many gases that are generated from anaerobic fermentation of manure and emitted from livestock and poultry confinement facilities. It is toxic and very dangerous when its sudden release from stored manure results in high concentrations in confined animal feeding operations (CAFO). Hydrogen sulfide has been responsible for many animal and human deaths in animal facilities (e.g., Oesterhelweg and Puschel, 2008). Carbon dioxide (CO_2), originating from animal respiration as well as from manure breakdown, is an important gas in confined animal buildings. Concentrations and emissions of CO_2 were sometimes used to estimate poultry house ventilation rates (e.g., Koerkamp et al., 1998; Liang et al., 2005). Particulate matter (PM) in poultry houses is also a concern for animal welfare, and occupational health and safety for farm workers (Banhazi et al., 2008).

* Corresponding author.
E-mail address: jiqin@purdue.edu (J.-Q. Ni).
[1] Current address: Vegetable Research Center, Beijing Academy of Agriculture and Forestry Sciences, China
[2] Current address: Biological and Agricultural Engineering, University of Idaho, USA
[3] Current address: School of Biosystems Engineering and Food Science, Zhejiang University, China
[4] Current address: Agricultural and Biosystems Engineering, South Dakota State University, USA
[5] Current address: Food Systems and Bioengineering, University of Missouri, USA

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Most of the published research on air quality at layer hen houses was conducted with survey-type investigations (e.g., Koerkamp et al., 1998) or short-time measurements (e.g., Green et al., 2009; Dobeic and Pintaric, 2011). Survey-type studies usually employ simple measurement techniques. Short-time measurements typically depict a small part of the actual pollution picture and cannot adequately cover diurnal and seasonal variations, which are critical characteristics of pollutant concentrations and house ventilation. Long-term and continuous monitoring is therefore needed to obtain the most in-depth knowledge in this research field.

In the U.S. National Air Emission Monitoring Study (NAEMS), air pollutant emissions from eight layer hen houses were monitored continuously for two years using state-of-the-science methodologies and technologies (Heber et al., 2008). The NAEMS generated the largest agricultural air quality datasets, which have been reported to U.S. Environmental Protection Agency (EPA). The NAEMS' layer hen sites in California (Lin et al., 2012) and North Carolina (Wang-Li et al., submitted for publication) each consisted of monitoring at two commercial houses. The monitoring of the two layer hen sites in Indiana was conducted at four houses on the same farm, representing the most comprehensive air quality investigation in layer houses. Based on the study in Indiana, a few research papers on gas sampling (Chai et al., 2010), fan monitoring (Chen et al., 2010), and ventilation calculation (Chai et al., 2012) have been published. However, new knowledge can still be acquired from the comprehensive datasets for the benefits of indoor air pollution research.

The objective of this article is to study the characteristics of air pollutant concentrations of NH_3, H_2S, CO_2, and PM_{10} in two types of layer hen houses at the NAEMS monitoring sites in Indiana. The scope of this article is limited to reporting pollutant concentrations at the air inlets of the house ventilation fans. Pollutant emissions will be published elsewhere.

2. Materials and methods

2.1. Layer houses

The commercial egg production farm consisted of an egg-processing plant, two high-rise (HR) caged-hen houses, seven manure-belt (MB) caged-hen layer houses, two cage-free layer houses, and one free-standing manure shed. Air pollutant concentrations and emissions were monitored at two HR houses (denoted here as H-A and H-B), two of the MB houses (B-A and B-B), and the manure shed (Fig. 1). The main characteristics of the four houses and the shed are listed in Table 1.

2.1.1. High-rise houses

In the two HR houses, birds were raised in ten rows of five-tier A-frame cages at cage level or upper floor (Fig. 2), and were molted according to industry standards. The lights at cage level were shut off for 8 h each night. Manure dropped off slanted boards behind the cages directly into the manure pit or first floor, where it was stored for up to one year or more.

Ventilation air entered the cage level from the attic through three temperature-adjusted V-shaped baffled ceiling air inlets in three zones of control. There were 55 belt-driven exhaust fans of 122-cm diameter (Model AT481Z1CP, Aerotech Inc., Mason, MI, USA) distributed along the west sidewall and 55 along the east sidewall, operated in 13 stages. Five fans were variable-speed as the first stage and other 50 fans were single-speed assigned to the remaining 12 stages.

Each house had 12 temperature sensors that were distributed at almost equal distances at cage levels and connected to the ventilation control systems (Table 1). Fifty circulation fans in the manure pit assisted in drying the manure.

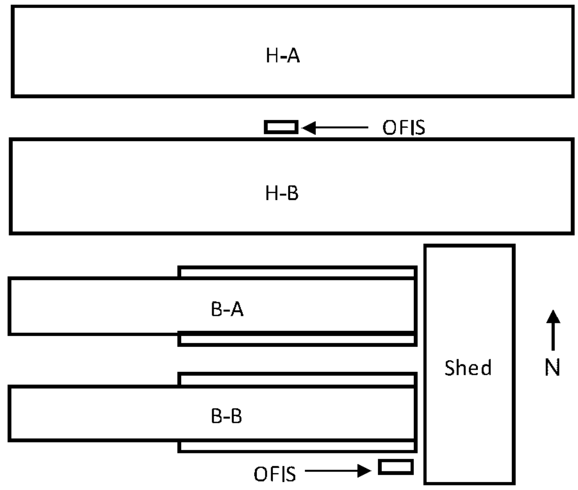

Fig. 1. Layout of the monitoring houses, manure shed, and on-farm instrument shelters (OFIS).

2.1.2. Manure-belt houses

In the MB houses, birds were raised in seven rows of ten-tier cages and were molted according to industry standards (Fig. 3). Manure was collected on 1.21-m wide plastic belts under each tier of cages. The belt system was manually-operated for approximately

Table 1
Characteristics of the houses and manure shed.

Descriptive parameter	H-A and H-B	B-A and B-B	Shed
House and shed type	High-rise	Manure-belt	Free-standing
Year of construction	1997	2004	2004
Monitoring start date	June 1, 2007	Jan. 1, 2008	Jan. 1, 2008
Monitoring end date	May 31, 2009	Dec. 31, 2009	Dec. 31, 2009
House length ┘ width (m)	198 ┘ 30.5	140 ┘ 19.5	61 ┘ 30.5
Ridge and sidewall height (m)	8.5 and 5	11.5 and 7	11.5 and 7
House orientation	EeW	EeW	NeS
Manure pit height (m)	2.4	e	e
House spacing (m)	17	18	3
Actual number of birds (A/B) (n)	217,800/218,300	250,100/ 246,000	e
Average weight (A/B) (kg)	1.44/1.46	1.42/1.41	e
House occupation (A/B)[a] (d)	717/718	731/713	e
Bird strain	W36	W36	e
Number of tiers and rows of cages	5 tiers and 10 rows	10 tiers and 7 rows	e
Type of cages	Big Dutchman 520 N	Facco	e
Manure accumulation (d)	365 or more	3	100e180
Manure collection method	Skid loader	Belts	Belts
Ventilation type	Mechanical	Mechanical	Natural
Number of ventilation stages (n)	13	13	e
Variable- and single-speed fans (n)	10 and 100	14 and 74	e
Walls with fans	N, S	N, S, E	e
Fan manufacturer and fan diameter	Aerotech, 122 cm	Aerotech, 132 cm	e
Number of pit circulation fans (n)	50	e	e
Number and type of air inlets	3 ceiling V-shape baffles	7 ceiling flat baffles	3 open slots
Inlet control basis/ adjustment method	Temperature/ cable	Temperature/ cable	e
Number of temperature sensors (n)	12	12	e
Control system manufacturer	Fancom	Fancom	e

[a] Days when the houses were 75% full.

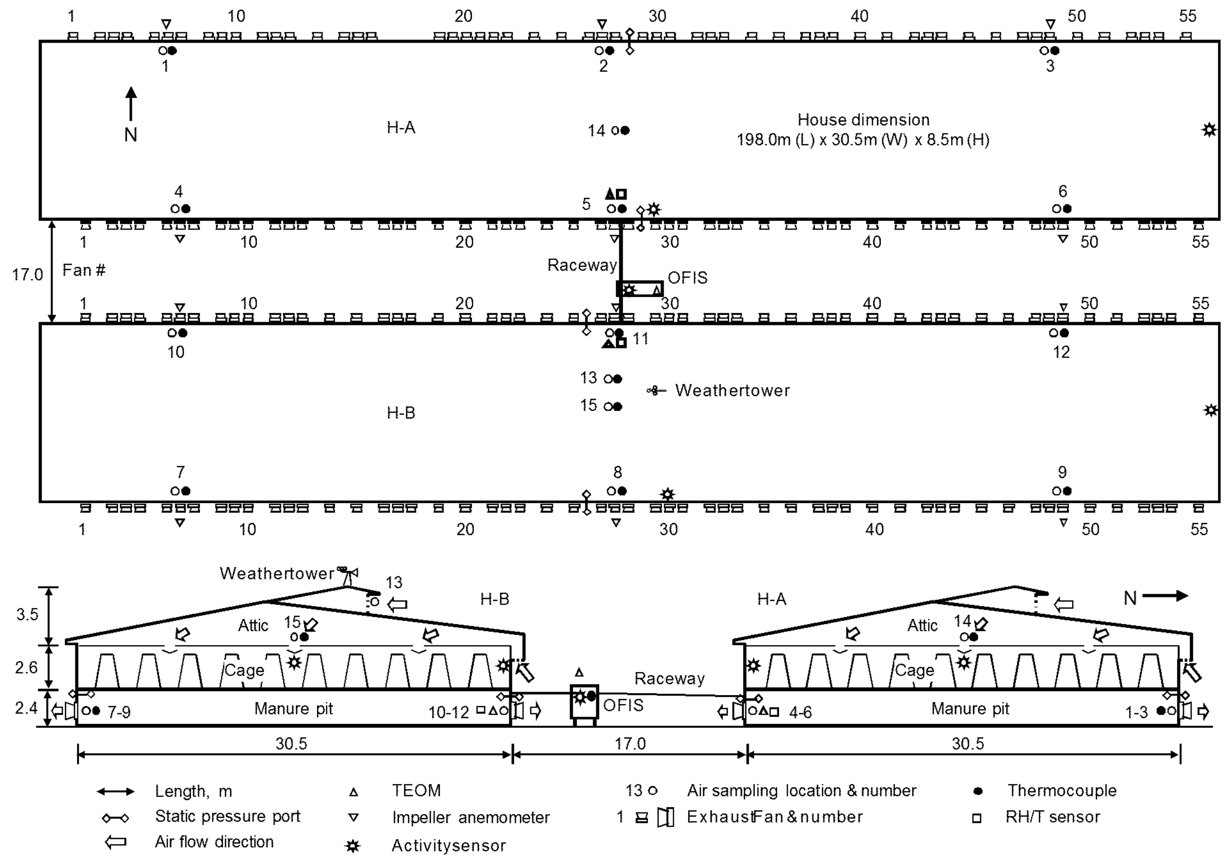

Fig. 2. Floor plan (top) and cross-sectional east-side view (bottom) of the high-rise houses with approximate measurement and sampling locations.

4 h in the morning each day, except for Sundays, to move the manure about 1/3 of the house length from west to east. The longest time that any manure stayed in the house was 4 d. The manure was then conveyed into manure drying tunnels by three belts at the east end of the house.

The drying tunnels were located in front of 13 or 14 exhaust fans, which assisted in drying the manure (Fig. 3). One side of the tunnel drying belts faced the ventilation fans on the house sidewall. Air from these fans flowed through the tunnel manure conveyor belts to the outside of the houses. The dried manure from the tunnels was transferred to the shed via other conveyer belts.

Ventilation air entered the cages from the attic through seven temperature-adjusted baffled ceiling air inlets, one over each row of cages. There were 88 exhaust fans of 132-cm diameter (Model VX511F3CR, Aerotech Inc, Mason, MI, USA) in each house, 40 in the north sidewall, 40 in the south sidewall, and 8 in the east endwall. The distribution of the fans in B-A and B-B were almost identical except for Fans 20e33 (Fig. 3). There were 14 variable-speed fans on north and south sidewalls that operated continuously in each house. The remaining 74 of the 88 exhaust fans were single-speed fans that were grouped into 12 ventilation stages. Two temperature-based ventilation control systems (Fancom, Panningen, The Netherlands) controlled all the variable- and single-speed fans. Each system controlled 44 fans in half of the house, i.e., 40 fans on one sidewall and 4 fans on the east wall.

2.2. Instrument shelters

Two on-farm instrument shelters (OFIS) were setup to house instruments, calibration gas cylinders, computers, sensors, tools, and office space at the monitoring sites (Figs. 1e3). One OFIS was between H-A and H-B and the other was near the southeast corner of B-B. The inside OFIS temperature was maintained high enough above the dew point to prevent condensation in sample tubing, but also low enough not to effect the operation of the analytical instruments and the electronics.

2.3. Temperature and ventilation monitoring

Temperature in the layer houses and manure shed were measured with relative humidity and temperature (RH/T) sensors and thermocouples. An RH/T sensor was located with each PM measurement instrument. Thermocouples (T-type) were used to measure temperatures at each gas sampling location that did not have an RH/T sensor.

House ventilation was monitored with several different techniques. All the ventilation fans were monitored individually and continuously either by vibration sensors (Model OSU-06, Ohio State University, Columbus, OH, USA), magnetic proximity sensors (Model MP100701, Cherry Co., Pleasant Prairie, WI, USA), and/or impeller anemometers (Model 27106RS, R.M. Young Company, Traverse City, MI, USA). House differential pressures, which were used to calculate fan airflow rates, were continuously measured across each wall that contained fans, and across the sidewalls and drying tunnels in B-A and B-B. The pressures were measured using pressure sensors (Model 260, Setra Systems, Inc., Boxborough, MA, USA) with a measurement range of └ 100 to þ100 Pa. Details about ventilation monitoring and calculation at B-A and B-B were described by Chai et al. (2012).

2.4. Gaseous pollutant monitoring

Air samples for continuous gas concentration measurements were collected from multiple gas sampling probes with a custom-

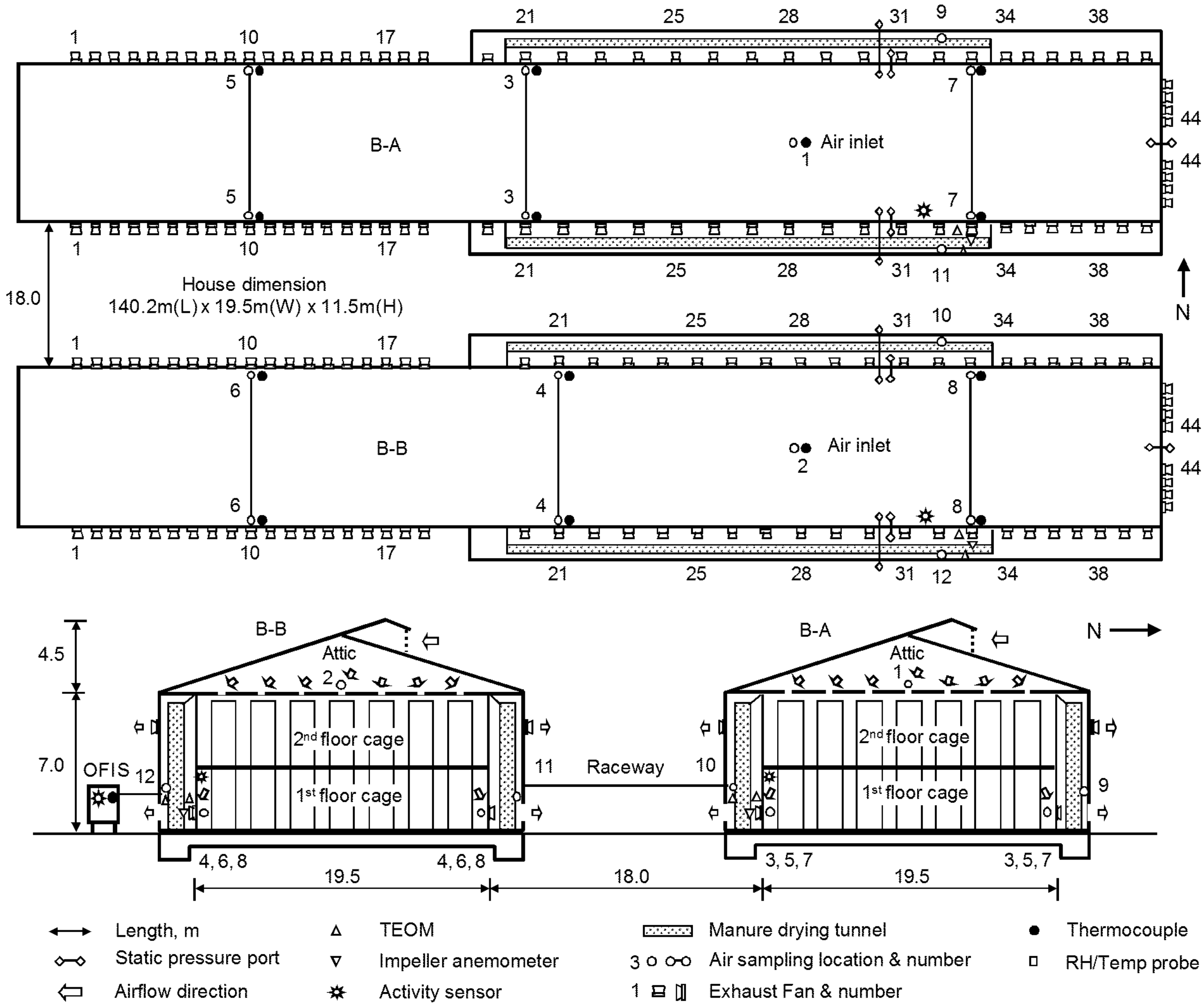

Fig. 3. Floor plan (top) and cross-sectional east-side view (bottom) of the manure-belt houses with approximate sampling and measurement locations.

designed gas sampling system (GSS). One set of gas analyzers in each OFIS measured gas concentrations as the GSS sequenced through all the gas sampling locations (GSL). All sampling probes were connected to the GSS with Teflon tubing.

There were 15 GSL in H-A and H-B (Table 2). Twelve of the GSL were at the inlets of the pit ventilation fans. One GSL (#13) sampled outdoor air at the house roof top (Fig. 2). Two others (#14 and #15) were set up for house inlet air. There were 13 GSL in B-A and B-B, and the Shed (Table 2 and Fig. 3). Two of them (#1 and #2) were for house inlet air in the attics. Six GSL (#3e#8) sampled exhaust air from the houses by compositing one north fan and one south fan sampling probes in one GSL. There were also 4 GSL for sampling air at the exhausts of each manure-drying belt, and one for the Shed exhaust air.

The sampling location, duration at each location, and sequence of all locations were controlled automatically or manually. In the automatic mode, the sampling duration was 20 min for the first air inlet location and 10 min for all the other locations.

Concentrations of NH_3 and CO_2 in the sampling air were measured with one multi-gas photoacoustic Field Gas-Monitor (Innova Model 1412, LumaSense Technologies, Ballerup, Denmark) at each site. Hydrogen sulfide was measured with a H_2S analyzer that consisted of a Model 43 analyzer and a Model 340 converter (Thermo Electron Co., Franklin, MA, USA) at the HR site. A newer Model 450i analyzer (Thermo Electron Co.), which housed both analyzer and converter in the same module, was used at the MB site.

A multi-point calibration was initially conducted for each gas analyzer to ensure response linearity with zero air and certified calibration gases using a gas diluter (Model S-4040, Environics, Tolland, CT, USA). Precisions of the gas analyzers were checked weekly during the study with the zero air and calibration gases.

Table 2
Gas sampling locations (GSL) and PM sampling locations (PMSL) at the two sites.

High-rise site			Manure-belt site		
Location	GSL #	PMSL #	Location	GSL #	PMSL #
H-A fan N 6	1		B-A attic air inlet	1	
H-A fan N 27	2		B-B attic air inlet	2	
H-A fan N 49	3		B-A fans N and S 21	3	
H-A fan S 6	4		B-B fans N and S 21	4	
H-A fan S 27	5	1	B-A fans N and S 10	5	
H-A fan S 49	6		B-B fans N and S 10	6	
H-B fan S 6	7		B-A fans N and S 33	7	
H-B fan S 27	8		B-B fans N and S 33	8	
H-B fan S 49	9		B-A N drying tunnel	9	
H-B fan N 6	10		B-B N drying tunnel	10	
H-B fan N 27	11	2	B-A S drying tunnel	11	
H-B fan N 49	12		B-B S drying tunnel	12	
H-B roof top	13		Manure shed east wall	13	1
H-A attic air inlet	14		B-A fan S 33		2
H-B attic air inlet	15		B-B fan S 33		3
1.2 m above OFIS roof		3	B-A S drying tunnel		4
			B-B S drying tunnel		5

2.5. Particulate matter monitoring

The Tapered Element Oscillating Microbalance, or TEOM (Model 1400a, Thermo Fisher Scientific), continuously sampled and measured PM concentrations at selected fan exhausts and the background outdoor conditions. Two TEOM units were used in H-A and H-B at about 1 m from the inlets of selected fans, one at fan S 27 in H-A and another at fan N 27 in H-B. The ambient air was sampled at 1.2 m above the OFIS roof between H-A and H-B with a third TEOM unit (Table 2 and Fig. 2).

In B-A and B-B, two TEOM units were positioned in the enclosed space between the exhaust fan side of fan S 33 and the manure drying tunnel in each house. Two additional TEOM units were located outside the south manure drying tunnel, directly downstream from fan S 33 in each house (Table 2 and Fig. 3). A beta attenuation PM monitor (Beta Gauge Model FH62C-14, Thermo Fisher Scientific) was set up in a platform in the shed, just south of the east wall entrance/exit door. The monitoring data from the two additional TEOM units and the Beta Gauge will be reported elsewhere.

2.6. Other monitoring

Data on bird inventory and mortalities were recorded manually on a daily basis by the producer and provided to the researchers on weekly data sheets. Weather conditions, including solar radiation, RH, T, wind speed, and wind direction, were monitored using a 1-m aluminum roof-top weather tower mounted on H-B (Fig. 2).

Infrared activity sensors (Visonic SRN 2000 Detector, Visonic Inc., Bloomfield, CT, USA) were mounted to walls or support posts in the houses to monitor movements of birds and workers.

2.7. Data acquisition, system control, and data processing

An on-site computer system (OSCS) was installed in each OFIS (Ni and Heber, 2010). The OSCS consisted of a personal computer, custom software AirDAC written in LabVIEW (National Instruments Co., Austin, TX, USA), and I/O hardware from National Instruments Co. and Measurement Computing Co. (Norton, MA, USA). All on-line measurement instruments and sensors were connected to the OSCS. The AirDAC converted the signals to engineering units, averaged them over 15-s and 60-s intervals, recorded the means into two separate computer files, and processed daily data files.

Post-measurement data processing was performed using custom software CAPECAB (Fibre Recovery Systems, Inc., Calgary, AB, Canada) (Cortus et al., 2010). To avoid bias in calculation, only days with more than 18 h (or 75%) of valid data were used to calculate daily, annual, and biannual means. Data presented in this article were from June 1, 2007 to May 31, 2009 for the HR site, and from January 1, 2008 to December 31, 2009 for the MB site (Table 1). Standard deviations and 95% confidence intervals of the pollutant concentrations were calculated on daily means.

3. Results and discussion

3.1. Temperature and ventilation at high-rise site

The 2-year mean cage-level temperatures were 27.5 ± 2.5 and 25.8 ± 2.3 °C (mean ± standard deviation) for H-A and H-B, respectively. Temperature in H-A was higher than that in H-B during the second year of monitoring probably due to molting in H-B (Fig. 4). The 2-year mean outdoor temperature was 12.4 ± 11.3 °C. The maximum and minimum daily mean outdoor temperatures were 29.8 and −18.4 °C, respectively. The outdoor temperatures during the study reflected typical weather conditions in the region.

Daily mean house ventilation rates ranged from 13.6 to 694.2 $m^3 s^{-1}$ at H-A and from 32.7 to 724.0 $m^3 s^{-1}$ at H-B. The 2-year mean ventilation rates were 185 ± 172 and 202 ± 187 $m^3 s^{-1}$, or 3.02 ± 2.73 and 3.08 ± 2.93 $m^3 h^{-1} hen^{-1}$, for H-A and H-B, respectively, and were not different ($P > 0.05$). The maximum ventilation rates occurred at the beginning of August 2007, when the hen-specific rate was about 11 $m^3 h^{-1} hen^{-1}$. The house ventilation rates were closely and inversely correlated to outdoor ambient temperature. Seasonal variations are clearly demonstrated in Fig. 4.

3.2. Temperature and ventilation rate at manure-belt site

The daily mean indoor air temperatures ranged from 20.0 to 31.0 °C in B-A and 14.9 to 31.2 °C in B-B. The lowest indoor daily

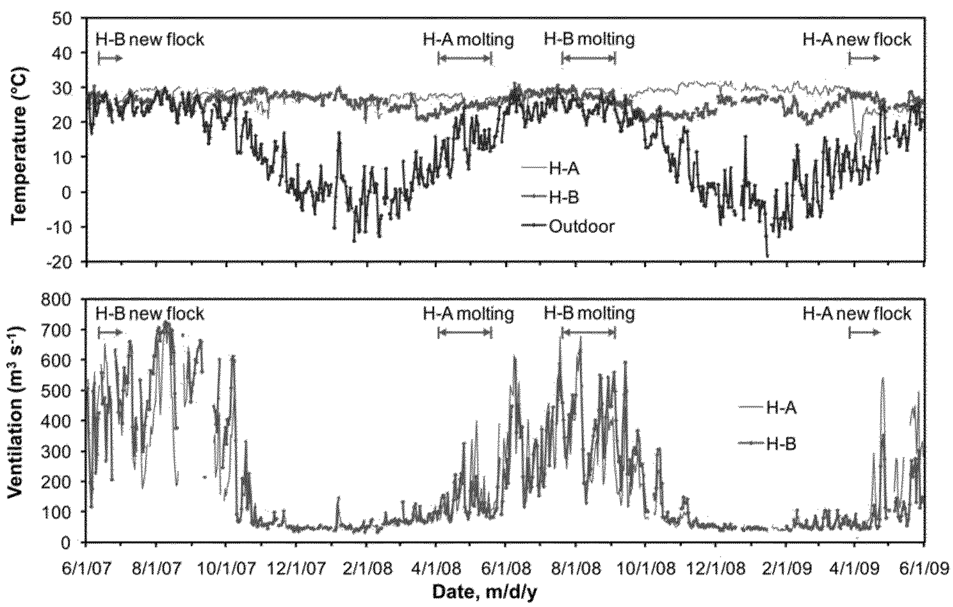

Fig. 4. Daily mean cage and outdoor temperatures, and house ventilation rates at the high-rise site.

mean temperature, close to 15 °C in B-B, occurred in October 2008 when the house was emptied between flocks of birds (Fig. 5). The highest daily mean indoor temperatures of about 31 °C were observed in July and August in both 2008 and 2009 during full-house days in the two houses. The 2-year mean indoor temperatures in B-A and B-B were 26.8 ± 2.0 and 26.5 ± 2.5 °C, respectively, while the 2-year mean outdoor temperature was 12.0 ± 10.9 °C.

The temperature differences between the two houses were the largest from October 2008 to March 2009, when an old flock of birds was removed from B-B, and a new flock was placed. The daily mean indoor temperatures showed seasonal variations corresponding to seasonal variations of outdoor temperatures. The indoor temperatures were mainly affected by the number of hens in the house and controlled by house ventilation.

The 2-year mean ventilation rates in B-A and B-B were 145 ± 107 and 142 ± 104 $m^3 s^{-1}$, or 2.08 ± 1.53 and 2.10 ± 1.55 $m^3 h^{-1} hen^{-1}$, respectively (Fig. 5). They were not statistically different ($P > 0.05$). However, compared with H-A and H-B, the ventilation per hen in B-A and B-B were lower (HR vs. MB, $P < 0.05$). Ventilation rates were generally higher from June to August than in other months of the year due to higher outdoor temperatures. The minimum daily mean ventilation rates were 0.59 and 0.81 $m^3 h^{-1} hen^{-1}$ for B-A and B-B, respectively. The maximum daily means were 9.16 and 9.22 $m^3 h^{-1} hen^{-1}$ for B-A and B-B, respectively. The daily mean ventilation rates per hen generally followed seasonal outdoor temperature variations.

3.3. Ammonia concentration

Valid data days for NH_3 concentrations in each house ranged from 625 d in H-A to 668 d in B-A (Table 3). The 2-year mean exhaust concentrations were 280% higher in the HR houses (48.9 ± 39 ppm in H-A and 51.9 ± 40.7 ppm in H-B) than in the MB houses (13.3 ± 9.1 ppm in B-A and 12.9 ± 10.5 in B-B), although the HR houses had higher ventilation per hen. The concentration differences were statistically significant between the two types of house designs (HR vs. MB, $P < 0.05$), but were insignificant between the two houses of the same design (HA vs. HB and BA vs. BB, $P > 0.05$). Similarly, the maximum daily mean NH_3 concentrations were also much higher in the HR houses (Fig. 6) than in the MB houses (Fig. 7), although the minimum daily mean concentrations in the two types of houses were about the same. However, previous research revealed that there were evident NH_3 concentration gradients following the west to east manure-belt movement in the same MB houses (B-A and B-B) (Chai et al., 2010). In other two NAEMS' HR layer houses monitored in North Carolina, significant NH_3 concentration gradients between the fan exhausts at east and west endwalls, and between the fan exhausts on two floors at the same endwall were also observed (Wang-Li et al., submitted for publication).

Although the NH_3 concentrations were obtained at the ventilation fans at both sites, the fans at the HR houses were in the first-floor manure pits, while the fans at the MB houses were at the cage level (Figs. 2 and 3). Because NH_3 originates from manure that existed in both cage and pit levels, when air flowed from the attics to the ventilation fans in H-A and H-B, NH_3 released from the manure in the pits could greatly increase the NH_3 concentrations in the air. Therefore, NH_3 concentrations in the cage levels should have been lower than detected at the fan exhausts in the HR houses. The concentrations at fan exhausts in the HR houses should not be used to suggest exposure to birds and workers.

Seasonal concentration variations (Figs. 6 and 7) were closely related to variations of outdoor temperatures and house ventilation rates, which are presented in Figs. 4 and 5. At higher outdoor temperatures and ventilation rates, NH_3 concentrations in the exhaust air were greatly reduced. However, NH_3 concentrations also depended on the NH_3 production that could be affected by bird age and molting. During the first month of a new flock or when the hens were molting, NH_3 concentrations were lower compared with the paired house under normal operational conditions. During the molting periods, the birds were provided with limited feed, resulting in greatly reduced manure production and NH_3 production.

Ammonia concentrations in poultry houses are usually higher than in other animal houses, e.g., dairy and swine (Koerkamp et al., 1998). An early study in the UK measured NH_3 concentrations as high as 160 ppm in broiler houses, and correlated the concentrations with humidity and ventilation (Valentine, 1964). A laboratory study by Ni et al. (2010) and a field monitoring by Dobeic and Pintaric (2011) also demonstrated the effect of layer manure moisture on higher NH_3 releases from manure.

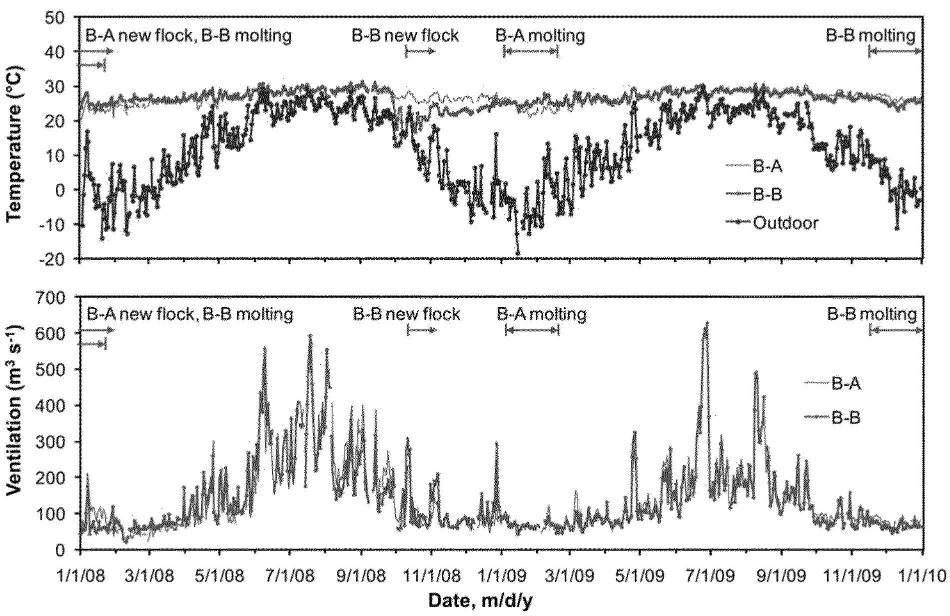

Fig. 5. Daily mean house and outdoor temperatures, and house ventilation rates at the manure-belt site.

Table 3
Selected statistics of gases and PM_{10} concentrations at exhaust fans.

	H-A		H-B		B-A		B-B	
Ammonia								
Valid days (n)	625		631		668		667	
Min. daily mean (ppm)	0.5		1.2		1.1		0.2	
Max. daily mean (ppm)	175.7		182.0		61.3		57.2	
1st yr mean (ppm)[a]	49.9	39.6	55.5	44.2	14.6	10.2	12.0	10.2
2nd yr mean (ppm)[a]	47.7	38.3	48.0	36.2	12.0	7.8	13.8	10.6
2-yr mean (ppm)[a]	48.9	39.0	51.9	40.7	13.3	9.1	12.9	10.5
2-yr mean (ppm)[b]	48.9	3.1	51.9	3.2	13.3	0.7	12.9	0.8
Hydrogen sulfide								
Valid days (n)	385		378		679		679	
Min. daily mean (ppb)	3.2		2.0		6.0		0.0	
Max. daily mean (ppb)	82.4		87.2		123.0		211.0	
1st yr mean (ppb)[a]	36.3	17.9	38.2	18.1	47.2	23.7	33.1	22.6
2nd yr mean (ppb)[a]	16.6	10.3	11.9	7.1	33.4	15.6	48.6	36.4
2-yr mean (ppb)[a]	26.4	17.6	24.9	19.0	40.0	21.1	41.2	31.5
2-yr mean (ppb)[b]	26.4	1.8	24.9	1.9	40.0	1.6	41.2	2.4
Carbon dioxide								
Valid days (n)	605		612		666		666	
Min. daily mean (ppm)	596		522		747		418	
Max. daily mean (ppm)	3763		4064		4972		4663	
1st yr mean (ppm)[a]	1711	827	1781	910	2258	898	2222	993
2nd yr mean (ppm)[a]	1804	869	1830	859	2330	843	2344	896
2-yr mean (ppm)[a]	1755	848	1804	887	2295	871	2285	946
2-yr mean (ppm)[b]	1755	68	1804	70	2295	66	2285	72
PM_{10}								
Valid days (n)	544		524		362		474	
Min. daily mean (mg m^{L3})	1		3		0		0	
Max. daily mean (mg m^{L3})	1719		3270		2702		4039	
1st yr mean (mg m^{L3})[a]	473	285	443	203	438	393	929	778
2nd yr mean (mg m^{L3})[a]	616	305	668	408	402	447	629	516
2-yr mean (mg m^{L3})[a]	540	303	552	338	415	428	761	661
2-yr mean (mg m^{L3})[b]	540	26	552	29	415	44	761	60

[a] Mean standard deviation.
[b] Mean 95% confidence interval.

Ammonia concentrations were related to house types. The HR design with in-house deep manure storage was coupled with higher NH_3 concentrations, which confirmed previous reports (e.g., Liang et al., 2005) and the NAEMS site in North Carolina (Wang-Li et al., submitted for publication). Compared with reports from other countries, e.g., 8.3 ppm in England, 29.6 ppm in the Netherlands, and 25.2 ppm in Denmark (Koerkamp et al., 1998); and 36.7 ppm in Slovenia (Dobeic and Pintaric, 2011), the 2-year mean concentrations at the exhaust fans in the HR houses were higher, but those in the MB houses were comparable. In Taiwan, a recent study showed NH_3 concentrations in hen cages ranged from 0.5 to 12.5 ppm (Cheng et al., 2011), which was also comparable to the MB houses in this study. However, concentrations from manure disposal sites were detected as high as 500 ppm at 10 cm above the manure surface (Cheng et al., 2011).

Exposure to high NH_3 concentrations has negative impacts on birds. Early studies in the 1960s revealed that layer hens exposed at 105 and 103 ppm NH_3 significantly reduced egg production and feed intake (Charles and Payne, 1966). To protect workers' health, different exposure limits were established in USA. The U.S. Department of Labor, Occupational Safety and Health Administration (OSHA) set the Permissible Exposure Limit (PEL) for general industry at 50 ppm time-weighted average (TWA) over 8 h. The Recommended Exposure Limit (REL) by National Institute for Occupational Safety and Health (NIOSH) and the Threshold Limit Value (TLV) by American Conference of Governmental Industrial Hygienists (ACGIH) were both 25 ppm TWA and 35 ppm short-term exposure limit (STEL, over 15 min) TWA (OSHA, 2003). The Taiwan legal labor exposure limits are 50 ppm for 8-h TWA and 75 ppm for STEL (Cheng et al., 2011). In Sweden, the NH_3 exposure limit for animals in the barn is 10 ppm (Anonymous, 2010). Although this study did not provide cage-level NH_3 concentrations in the HR houses, a large portion of daily mean NH_3 concentrations in winter in the MB houses exceeded 25 ppm and 35 ppm levels, which showed potential concerns for animal welfare and workers' health.

3.4. Hydrogen sulfide concentration

The number of valid data days for H_2S concentrations in each house ranged from 378 d in H-B to 679 d in B-A and B-B (Table 3). The low number of valid data days in the HR site was due to higher maintenance and repair requirements of the 10-year old analyzer compared with the newer analyzer in the MB site. The 2-year mean H_2S concentrations in the HR houses (26.4 17.6 ppb in H-A and 24.9 19.0 ppb in H-B) were lower than in the MB houses (40.0 21.1 ppb in B-A and 41.2 31.5 in B-B). Similarly, the maximum daily mean H_2S concentrations were also lower in the HR houses than in the MB houses. The daily mean H_2S concentrations presented in Figs. 6 and 7 demonstrate seasonal variations and also show an inverse relationship to house ventilation rates. The effects of temperature and ventilation on H_2S concentrations were not as profound as on NH_3 concentrations. However, it appeared that, like NH_3 concentrations, molting of birds also reduced the H_2S concentrations in B-A. The H_2S concentration differences were statistically significant between the two types of house designs ($P < 0.05$), but were insignificant between the two houses of the same design ($P > 0.05$).

Little information about H_2S concentrations in layer houses is available in the literature. The overall mean exhaust air H_2S concentrations of 19.7 ppb in a HR commercial layer house reported by Lim et al. (2003) were close to the HR houses in this study. However, the 40e100 ppb H_2S concentrations detected by Zhu et al. (2000) in a broiler house were higher than this study. The H_2S concentrations in layer houses were much lower compared with commercial swine barns, which were 500e1000 ppb at normal operational conditions (Zhu et al., 2000), up to 14 ppm during shallow manure pit flushing (Lim et al., 2004), and as high as 36 ppm when manure was agitated during removal (Hoff et al., 2006). High H_2S concentrations of 10 ppm as 8-h TWA and 15 ppm as 15-min STEL by OSHA (2010); and 10 ppm REL for 10 min by NIOSH (2010) were not detected in this study.

3.5. Carbon dioxide concentration

Valid data days for CO_2 concentrations in each house ranged from 605 d in H-A to 666 d in B-A and B-B (Table 3). The 2-year mean concentrations in the HR houses (1755 848 ppm in H-A and 1804 887 ppm in H-B) were 80% of those in the MB houses (2295 871 ppm in B-A and 2285 946 in B-B). The differences were statistically significant ($P < 0.05$). The maximum daily mean CO_2 concentrations in the HR houses were also generally lower than in the MB houses. However, compared with NH_3, the differences in CO_2 concentrations between the two types of houses were less extensive.

The patterns of seasonal CO_2 concentration variations were very similar to those of NH_3 in all four houses (Figs. 6 and 7). The high daily mean concentrations were detected between January and March. July and August were the months with the lowest CO_2 concentrations. The higher daily mean CO_2 concentrations in B-A and B-B might have resulted from the lower ventilation rate per hen, as compared with H-A and H-B. The exceptionally low CO_2 concentrations in B-B at the end of Oct. 2008 were due to the empty house days between two flocks of birds.

The layer hen house CO_2 in this study exhibited a wide range of daily mean concentrations. They agreed with some reported values,

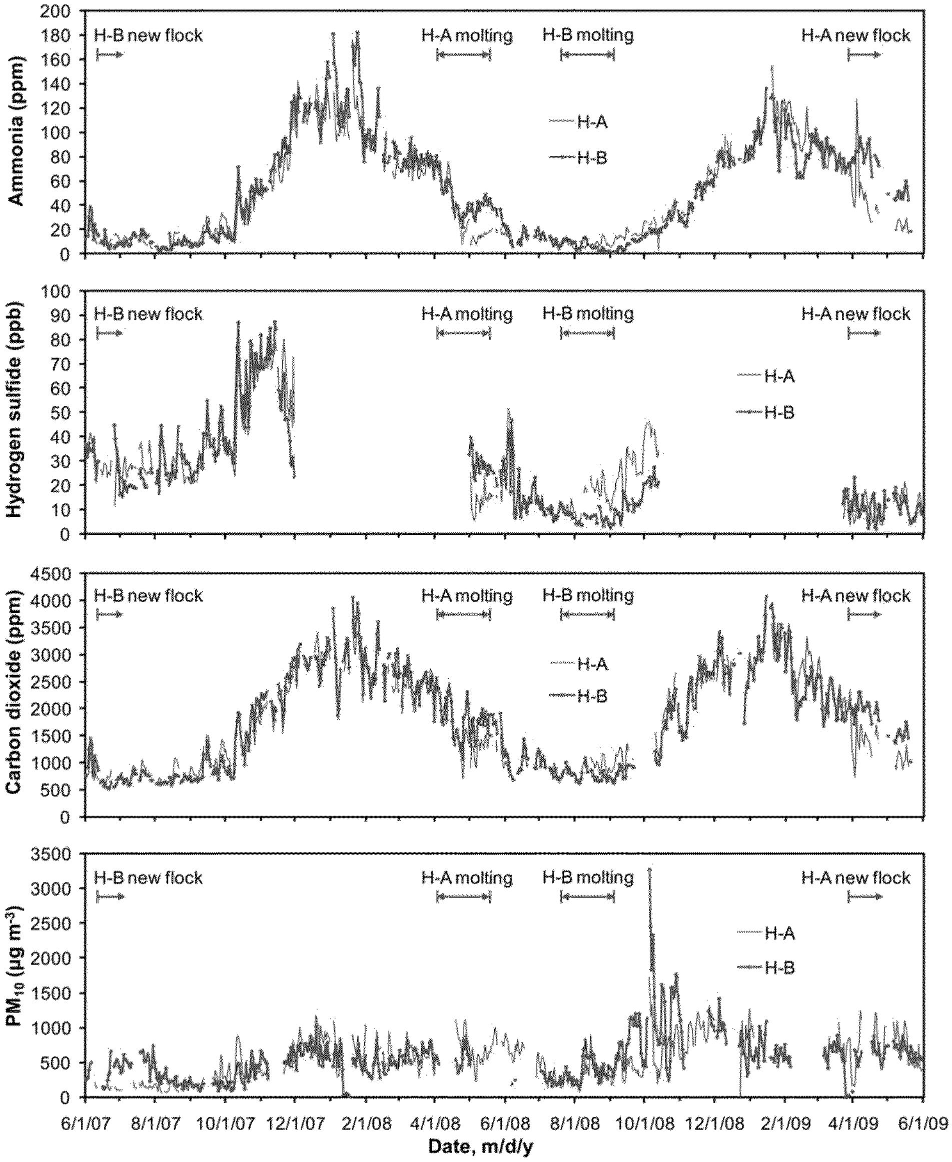

Fig. 6. Daily mean concentrations of ammonia, hydrogen sulphide, carbon dioxide, and PM$_{10}$ at high-rise site.

e.g., 210e4300 ppm in exhaust air streams (Liang et al., 2005), but were also differed than other reports. A recent survey of seven layer hen houses in Slovenia resulted in mean CO_2 concentrations of 758 ppm in exhaust air (Dobeic and Pintaric, 2011). In a study in Iowa with 20- to 24-h measurements in each house each season, the mean CO_2 concentrations were 3072 ppm in winter and 1012 ppm in summer in four MB houses. In four HR houses, the mean CO_2 concentrations were 2433 ppm in winter and 520 ppm in summer (Green et al., 2009). In three types of layer hen houses in Northern Europe with 1- to 2-week measurements, Nimmermark et al. (2009) obtained daily mean CO_2 concentrations from 1800 to 2500 ppm.

High CO_2 concentrations have a negative health effect on layer hens. In a laboratory chamber study, Helbacka et al. (1963) demonstrated that exposure of layer hens to 5% CO_2 concentration caused a drop in blood pH and reduction in shell thickness. However, the 5% CO_2 is about 10 times as high as the maximum daily mean concentration in B-A. Whether CO_2 at about 5000 ppm has negative effects on layer hen health is still not known and needs more investigation.

3.6. PM$_{10}$ concentration

Because the TEOM was originally designed for measuring relatively low outdoor PM concentrations, it was more susceptible to errors and failures when used in high PM concentration environments such as in the layer hen houses. Data completeness for PM$_{10}$ measurement in this study was not as good as that for gases. The number of valid data days for PM$_{10}$ concentrations in each house ranged from 362 d in B-A to 544 d in H-A (Table 3). The fewer valid days for PM$_{10}$ measurement, compared with other pollutants, was because of more frequent failure of the TEOM units, and that they were sometimes unavailable to measure PM$_{10}$.

The 2-year mean concentrations in H-A (540 303 μg m^{-3}) and in H-B (552 338 μg m^{-3}) were not statistically different ($P > 0.05$). However, in the MB houses the 2-year mean concentrations were 415 428 μg m^{-3} in B-A, much lower than the 761 661 μg m^{-3} in B-B ($P < 0.05$). Distribution of the valid data days in Figs. 6 and 7 shows that missing data affected the 2-year mean concentration in B-A. Therefore, concentrations in B-B were more representative for the entire monitoring period.

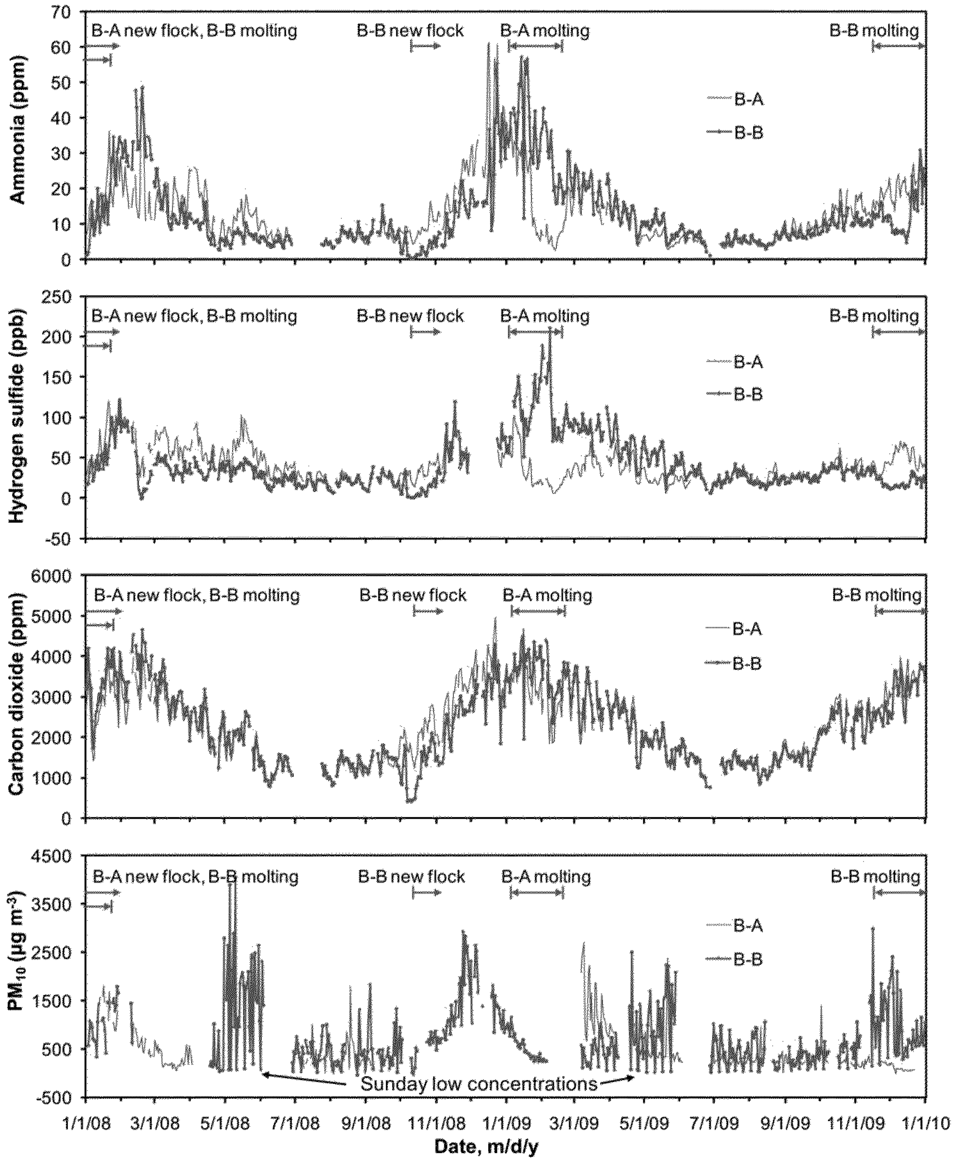

Fig. 7. Daily mean concentrations of ammonia, hydrogen sulphide, carbon dioxide, and PM_{10} at the manure-belt site.

Compared with H-A and H-B, the mean PM_{10} concentration in B-B was 38% higher ($P < 0.05$).

Dust concentrations in poultry houses vary greatly. They ranged from 0.3 to 1.2 mg m^{-3} for respirable dust (roughly equivalent to PM_{10}) (Wathes et al., 1997). Ellen et al. (2000) summarized ranges from 10 to 6500 μg m^{-3} for respirable dust. Houses with caged layer hens showed the lowest dust concentrations, compared with the other housing systems. Ellen et al. (2000) also discussed the factors affecting dust concentrations, including animal category, animal activity, bedding material, and season. The 2-year mean PM_{10} concentrations in this study were in the lower end of the range reported by Ellen et al. (2000), and closer to the 840 μg m^{-3} respirable particle concentrations obtained in a survey by Banhazi et al. (2008).

The daily mean exhaust air PM_{10} concentrations varied considerably between the houses (Figs. 6 and 7). The seasonal variations of PM_{10} concentrations were not as obvious as gas concentrations, especially in H-A and H-B. An interesting weekly variation of PM_{10} concentrations was demonstrated. This phenomenon was most visible in B-B (Fig. 7). Data analysis confirmed that the PM_{10} concentrations in B-B were the lowest on Sundays compared with weekdays and Saturdays. From April to Nov. 2008 and from March to Dec. 2009, the PM_{10} concentrations on Sundays were mostly < 100 μg m^{-3}. This was related to house operational activities. Sunday was the only day during the week that farm workers did not perform routine work, including operating the manure belt and manure conveyers that transported manure from the houses to the manure shed in the morning. More detailed analysis of the weekly air pollutant variations will be published elsewhere.

4. Conclusions

1. The higher NH_3, and lower CO_2, H_2S and PM_{10} concentrations obtained in the HR houses, compared with the MB houses, demonstrated that house design had considerable effects on indoor pollutant concentrations.
2. The high indoor NH_3 concentrations at the exhaust fans at the MB site during a considerable portion of winter days represent potential concerns for workers' and animals' health.

3. Seasonal patterns of NH_3 and CO_2 concentrations were more apparent compared with H_2S and PM_{10} concentrations. They were well correlated to temperature, ventilation rate, and animal conditions. This characteristic implies that indoor concentrations and emissions can be better modeled for NH_3 and CO_2 than for the other two pollutants.
4. In addition to the bird number and bird weight, this study also showed that new birds and birds under molting resulted in lower NH_3 and H_2S concentrations.
5. In addition to the well-known diurnal and seasonal variations for air pollutant concentrations and emissions, PM_{10} concentrations were identified to have a new and distinguished weekly variation pattern, which was related to farm operational activities. This finding expanded our understanding of temporal distribution of indoor air quality in animal buildings.
6. Long-term and continuous monitoring of air pollutants provided new insights into the characteristics of indoor air quality, which could not have been revealed in short-term monitoring. The knowledge obtained from the NAEMS will help to better understand potential health effects on workers and animals in egg production facilities.
7. The NAEMS layer hen monitoring sites in Indiana offered a unique opportunity for side-by-side comparisons of two types of layer hen house designs. It eliminated potential effects of different geographical locations and climate conditions, thus making the comparison results more reliable.
8. Technical problems experienced with the relatively more frequent failures of H_2S analyzer and TEOM units caused losses of data. High PM concentrations during layer house cleaning often exceeded the TEOM measurement ranges. Additionally, the limited number of PM_{10} sampling locations was a major restriction for studying PM spatial distributions. Solutions to these issues should be sought to improve future research.

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References

Anonymous, 2010. Statens jordbruksverks föreskrifter och allmänna råd om djurhållning inom lantbruket m.m. Jordbruks verket, Jönköping, 10 maj. 48 p.

Banhazi, T.M., Seedorf, J., Laffrique, M., Rutley, D.L., 2008. Identification of the risk factors for high airborne particle concentrations in broiler buildings using statistical modelling. Biosystems Engineering 101, 100e110. doi:10.1016/j.biosystemseng.2008.06.007.

Chai, L.-L., Ni, J.-Q., Chen, Y., Diehl, C.A., Heber, A.J., Lim, T.-T., 2010. Assessment of long-term gas sampling design at two commercial manure-belt layer barns. Journal of the Air & Waste Management Association 60, 702e710. doi:10.3155/1047-3289.60.6.702.

Chai, L., Ni, J.-Q., Diehl, C.A., Kilic, I., Heber, A.J., Chen, Y., Cortus, E.L., Bogan, B.W., Lim, T.-T., Ramirez-Dorronsoro, J.-C., Chen, L., 2012. Ventilation rates at large commercial layer houses with two-year continuous monitoring. British Poultry Science 53, 19e22. doi:10.1080/00071668.2011.643766.

Charles, D.R., Payne, C.G., 1966. The influence of graded levels of atmospheric ammonia on chickens. II. Effects on the performance of laying hens. British Poultry Science 7, 189e198.

Chen, Y., Ni, J.-Q., Diehl, C.A., Heber, A.J., Bogan, B.W., Chai, L., 2010. Large scale application of vibration sensors for fan monitoring at commercial layer hen houses. Sensors 10, 11590e11604. doi:10.3390/s101211590.

Cheng, W.H., Chou, M.S., Tung, S.C., 2011. Gaseous ammonia emission from poultry facilities in Taiwan. Environmental Engineering Science 28, 283e289. doi:10.1089/ees.2010.0205.

Cortus, E.L., Bogan, B., Wang, K., Lim, T.-T., Ni, J.-Q., Eisentraut, M., Eisentraut, P., Heber, A.J., 2010. Using CAPECAB to process emission data in the national air emissions monitoring study. In: International Symposium on Air Quality and Manure Management for Agriculture. ASABE Publication Number 711P0510cd. ASABE, St. Joseph, Mich.

Dawkins, M.S., Donnelly, C.A., Jones, T.A., 2004. Chicken welfare is influenced more by housing conditions than by stocking density. Nature 427, 342e344. doi:10.1038/nature02226.

Dobeic, M., Pintaric, S., 2011. Laying hen and pig livestock contribution to aerial pollution in Slovenia. Acta Veterinaria-Beograd 61, 283e293. doi:10.2298/AVB1103283D.

Ellen, H.H., Bottcher, R.W., vonWachenfelt, E., Takai, H., 2000. Dust levels and control methods in poultry houses. Journal of Agricultural Safety and Health 6, 275e282.

Green, A.R., Wesley, I., Trampel, D.W., Xin, H., 2009. Air quality and bird health status in three types of commercial egg layer houses. Journal of Applied Poultry Research 18, 605e621. doi:10.3382/japr.2007-00086.

Heber, A.J., Bogan, B.W., Ni, J.-Q., Lim, T.-T., Cortus, E.L., Ramirez-Dorronsoro, J.C., Diehl, C.A., Hanni, S.M., Xiao, C., Casey, K.D., Gooch, C.A., Jacobson, L.D., Koziel, J.A., Mitloehner, F.M., Ndegwa, P.M., Robarge, W.P., Wang, L., Zhang, R., 2008. The National Air Emissions Monitoring Study: overview of barn sources. In: The Eighth International Livestock Environment Symposium. Paper Number PAP-1459. ASABE, St. Joseph, Mich.

Helbacka, N.V., Smith, C.J., Casterline, J.L., 1963. Effect of high CO_2 atmosphere on laying hen. Poultry Science 42, 1082e1084.

Hoff, S.J., Bundy, D.S., Nelson, M.A., Zelle, B.C., Jacobson, L.D., Heber, A.J., Ni, J.-Q., Zhang, Y.H., Koziel, J.A., Beasley, D.B., 2006. Emissions of ammonia, hydrogen sulfide, and odor before, during and after slurry removal from a deep-pit swine finisher. Journal of the Air & Waste Management Association 56, 581e590.

Koerkamp, P.W.G.G., Metz, J.H.M., Uenk, G.H., Phillips, V.R., Holden, M.R., Sneath, R.W., Short, J.L., White, R.P., Hartung, J., Seedorf, J., Schroder, M., Linkert, K.H., Pedersen, S., Takai, H., Johnsen, J.O., Wathes, C.M., 1998. Concentrations and emissions of ammonia in livestock buildings in Northern Europe. Journal of Agricultural Engineering Research 70, 79e95.

Liang, Y., Xin, H., Wheeler, E.F., Gates, R.S., Li, H., Zajaczkowski, J.S., Topper, P.A., Casey, K.D., Behrends, B.R., Burnham, D.J., Zajaczkowski, F.J., 2005. Ammonia emissions from US laying hen houses in Iowa and Pennsylvania. Transactions of the ASAE 48, 1927e1941.

Lim, T.-T., Heber, A.J., Ni, J.-Q., 2003. Air quality measurements at a laying hen house: odor and hydrogen sulfide emissions. In: International Symposium on Control of Gaseous and Odor Emissions from Animal Production Facilities, Horsens, Denmark. Danish Institute of Agricultural Sciences, Foulum, Denmark, pp. 273e282.

Lim, T.-T., Heber, A.J., Ni, J.-Q., Kendall, D., Richert, B.T., 2004. Effects of manure removal strategies on odor and gas emission from swine finishing. Transactions of the ASAE 47, 2041e2050.

Lin, X.-J., Cortus, E.L., Zhang, R., Jiang, S., Heber, A.J., 2012. Ammonia, hydrogen sulfide, carbon dioxide and particulate matter emissions from California high-rise layer houses. Atmospheric Environment 46, 81e91. doi:10.1016/j.atmosenv.2011.10.021.

Ni, J.-Q., Heber, A.J., 2010. An on-site computer system for comprehensive agricultural air quality research. Computers and Electronics in Agriculture 71, 38e49. doi:10.1016/j.compag.2009.12.001.

Ni, J.-Q., Heber, A.J., Hanni, S.M., Lim, T.-T., Diehl, C.A., 2010. Characteristics of ammonia and carbon dioxide releases from layer hen manure. British Poultry Science 51, 326e334. doi:10.1080/00071668.2010.495977.

Nimmermark, S., Lund, V., Gustafsson, G., Eduard, W., 2009. Ammonia, dust and bacteria in welfare-oriented systems for laying hens. Annals of Agricultural and Environmental Medicine 16, 103e113.

NIOSH, 2010. Pocket Guide to Chemical Hazards: Hydrogen Sulfide. National Institute for Occupational Safety and Health, Washington, DC. November 18.

Oesterhelweg, L., Puschel, K., 2008. "Death may come on like a stroke of lightning . " e phenomenological and morphological aspects of fatalities caused by manure gas. International Journal of Legal Medicine 122, 101e107. doi:10.1007/s00414-007-0172-8.

OSHA, 2003. Safety and Health Topics: Ammonia. Occupational Safety and Health Administration, U.S. Department of Labor, Washington D.C.

OSHA, 2010. Hydrogen Sulfide in Workplace Atmospheres: Method Number ID-141. Occupational Safety and Health Administration, U.S. Department of Labor, Washington D.C.

Portejoie, S., Martinez, J., Landmann, G., 2002. L'ammoniac d'origine agricole: impacts sur la santé humaine et animale et sur le milieu naturel. Productions Animales 15, 151e160.

Valentine, H., 1964. A study of the effect of different ventilation rates on the ammonia concentrations in the atmosphere of broiler houses. British Poultry Science 5, 149e159.

Wang-Li, L., Li, Q.F., Bogan, B.W., Wang, K., Ni, J.-Q., Kilic, I., Heber, A.J., 2012. National air emissions monitoring study-southeast layer site: Part III e ammonia concentrations and emissions. Transactions of the ASABE, submitted for publication.

Wathes, C.M., Holden, M.R., Sneath, R.W., White, R.P., Phillips, V.R., 1997. Concentrations and emission rates of aerial ammonia, nitrous oxide, methane, carbon dioxide, dust and endotoxin in UK broiler and layer houses. British Poultry Science 38, 14e28. doi:10.1080/00071669708417936.

Zhu, J., Jacobson, L., Schmidt, D., Nicolai, R., 2000. Daily variations in odor and gas emissions from animal facilities. Applied Engineering in Agriculture 16, 153e158.